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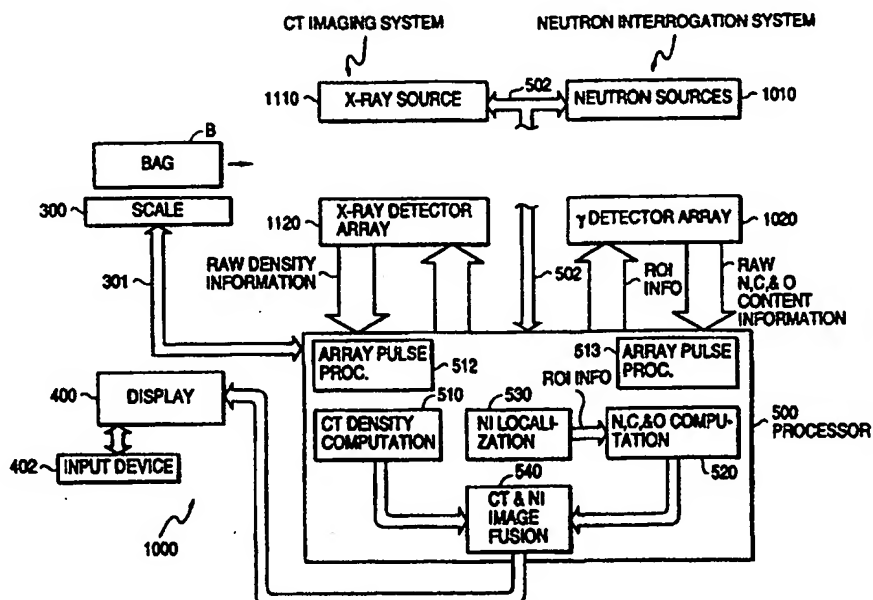


(57) Abstract

X-ray CT (computed tomography) and neutron interrogation (NI) are combined to provide an inspection system (100) and spatial
resolution technique for detecting explosives. X-ray CT (510) is used to derive a physical density map of a bag (B). The density map from
X-ray CT (510) and data from neutron interrogation (520) is used to generate three-dimensional maps of the chemical make-up of the bag
(B) contents. Information from the X-ray CT procedure is also used to focus the neutron interrogation on particularly suspect regions of
interest in the bag (B).

## INSPECTION SYSTEM AND SPATIAL RESOLUTION TECHNIQUE FOR DETECTING EXPLOSIVES USING COMBINED NEUTRON INTERROGATION AND X-RAY IMAGING

### Background of the Invention

5      The invention is directed to an inspection system and technique for the detection of explosives, for example, in luggage. More specifically, the invention is directed to an improved technique for the detection of explosives which uses a combination of neutron interrogation and X-

10     ray imaging.

The detection of hidden explosives in airline baggage is difficult. Small amounts of explosives must be identified with a high degree of certainty while at the same time a low level of disruption due to false

15     positives must be ensured. Approximately one pound of high explosives positioned within an airliner's cargo bay is sufficient to destabilize the plane. In the United States alone there are approximately $10^9$ bags checked per year. Six hundred bags may be loaded on a single

20     Boeing 747.

For reasons of throughput a one-hour period is typically allowed for baggage loading. It is therefore necessary that an inspection procedure last only about 6 seconds per bag. These requirements necessitate an

25     automated imaging system with a high spatial resolution, a low threshold for explosive detection, and a high resolution measurement signature that differentiates between explosives and other materials.

The detection technique must detect shaped moldable

30     plastic explosives such as PETN and others which result in a partial volume fill even for small volumes. Plastic explosives can be molded in combination with a camouflage material and can include shielding. Both the intrinsic explosive and the shielding should be identifiable

35     independently. Because high explosives almost exclusively have a particularly separate chemistry in terms of oxygen and nitrogen content, chemical make-up

constitutes a more certain signature than just density measurements based on X-ray inspection or measurement of hydrogen content (which is high for typical explosives) by means of NMR (nuclear magnetic resonance). NMR may experience problems with magnetic as well as conductive baggage contents and also does not provide a unique signature.

Various techniques have been suggested to detect explosives in airline baggage.

Detection on a purely chemical basis by explosive vapor detection has been suggested. However, this technique can easily be undermined by impermeable encapsulation covers.

Since explosives are relatively closely grouped in terms of physical density, X-ray CT (computed tomography) methods have been suggested. Although modern CT capabilities can identify shapes, contrasts, densities and contiguousness of feasibly shaped explosives, the standard process is very demanding in terms of the hardware required as well as the logistics of providing multiple view access and acceptable scan rates. X-ray CT methods do not provide a chemical signature. No X-ray CT system to date offers performance commensurate with reasonable field specifications.

The nuclear technique of PET (positron emission tomography) has been suggested. This technique provides an excellent signature analysis in that positron emission annihilation is detected by back-to-back synchronous monoenergetic photons of 511 keV. The chemicals of interest, $^{15}O$ and $^{13}N$ are producible by photoproduction with energetic $\gamma$ rays, and have 2 and 10 minute half-lives, respectively. Difficulties arise, however, in generating a sufficiently intense source, low photoproduction cross sections, and a relatively expensive double detector array setup with very fast acquisition and processing times to handle $\gamma$-$\gamma$ coincidences. The fairly sizable half-lives, and an additional 20 minute half-life for carbon, which

constitutes a great deal of background chemical, compared
to the available residence time of a bag in a detector do
not provide a clear identification of oxygen and nitrogen
density given the low rates of activation.

5        Neutron Interrogation (NI) provides a variety of
various techniques. It is possible to do attenuation and
scattering measurements although this requires several
distinct neutron incident energies in order to solve for
all of the abundant chemical species (typically H, C, N,
10      O, and others) in the explosive and other baggage
materials. The multiple energy requirement makes this
technique rather impractical.

If a pulsed beam is available with pulse definition
on the order of one nanosecond it is conceivable to do
15      neutron source to baggage reaction position neutron time-
of-flight measurements for localization using subsequent
prompt $\gamma$ emissions from various excited states. Here the
difficulty lies in the feasibility of nanosecond intense
pulse definition, a large source to baggage distance
20      which implies a very low fluence rate because typically
neutron sources emit isotropically, dealing with a
collimated neutron beam which means an even lower
fluence, and looking for $\gamma$'s forward in time in order to
preserve the time-of-flight separation, thus requiring a
25      limited exposure of baggage at any one time. The
background events associated with the setup also
deteriorate some of the elegant simplicity of using the
$(n,\gamma)$ prompt reactions due to accidental coincidences.

Associated particle production from the reaction
30      $^3H(d,n)^4He$ using 14 MeV neutrons is a potentially feasible
detection technique where the $\alpha$ particle is detected
within the neutron generating source with good position
resolution so as to provide a flight path of the neutron
on the opposite side. While this technique provides very
35      strong correlational information, individual events
timing and $\alpha$ and n detection to within several
nanoseconds must be accounted for, and therefore the
system must account for a low rate of accidentals and

background events.  These considerations result in a reduced source production rate which in turn yields a low rate of excitation and/or activation events due to limited cross sections.

5        Accordingly, there is a real need for an explosive detection system which is practical in terms of system cost and inspection time, and which at the same time provides for the detection of small amounts of shapeable explosives with high certainty and a low number of false
10       positives.

### Summary of the Invention

An object of the invention, therefore, is to provide an improved apparatus and technique for detecting explosives.

15       In the invention, X-ray CT (computed tomography) and neutron interrogation (NI) are combined to provide an inspection system and spatial resolution technique for detecting explosives.  X-ray CT is used to derive a physical density map of a bag.  The density map from X-
20       ray CT and data from neutron interrogation is used to generate multi-dimensional (i.e., two or three dimensional) maps of the chemical make-up of the bag contents.  Information from the X-ray CT procedure is also used to focus the neutron interrogation on
25       particularly suspect regions of interest in the bag.

According to one aspect of the invention there is provided an inspection system to inspect an object, such as luggage.  The inspection system includes a CT imaging system having an X-ray source and an X-ray detector array
30       and a neutron interrogation system having neutron sources and a gamma detector array.  The inspection system also includes a processor which is connected to the CT imaging system and to the neutron interrogation system.  The processor includes a density computation module to
35       generate a multi-dimensional density map of the object based on data from the CT imaging system and a chemical species computation module to generate a multi-dimensional map which indicates the concentration of at

least three elements (e.g., nitrogen, carbon and oxygen) in the object based on information from the neutron interrogation system and on density information from the density computation module.  The processor also includes a localization module to provide region-of-interest information for neutron interrogation based on information from the density computation module.

Information from the localization module can be used to focus neutron interrogation on high density areas within the object.  In addition, carbon measurements can be used for normalization of nitrogen and oxygen measurements to eliminate systematic errors common to carbon, nitrogen, and oxygen measurements.

According to another aspect of the invention there is provided a method of detecting explosives in an object.  The method includes irradiating the object with X-rays and measuring the attenuation and scattering of the X-rays in the object.  Information representing the density make-up of the object is generated based on this attenuation and scattering information.  The object is also irradiated with neutrons and the number and energy of gamma particles resulting from neutron-gamma reactions (abbreviated "$(n,\gamma)$") in the object are measured. Information regarding the presence or absence of explosives in the object is then generated based on the measurement of the gamma particles and on the density information.  The neutron interrogation can be focussed on high density areas within the object based on the density information.

Other objects, features, and advantages of the invention will become apparent from the detailed description of the invention set forth below.

Brief Description of the Drawings

The invention will be described in greater detail below with reference to the accompanying drawings, wherein:

Figure 1 illustrates an inspection system according to a preferred embodiment of the invention;

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Figure 2 illustrates an X-ray CT imaging system which is suitable for use in the inspection system of Figure 1;

Figures 3 and 4 illustrate the operation of the X-ray
5      CT imaging system of Figure 2;

Figure 5 illustrates a neutron interrogation system which is suitable for use in the inspection system of Figure 1;

Figure 6 illustrates a portion of the BGO (bismuth
10     germinate) pulse processing circuitry of Figure 5; and

Figure 7 is a flowchart which illustrates a specific application example of the present invention.

## Detailed Description of Preferred Embodiments

### Overview

15         The present invention combines functions of X-ray CT and neutron interrogation (NI). X-ray CT is used to derive a physical density map of an object such as a bag and NI is used to determine the chemical composition of regions within the object. The NI procedure uses the
20     density map from X-ray CT to generate and better resolve multi-dimensional maps, such as three dimensional maps, showing the chemical make-up of the bag contents.

Information from the X-ray CT procedure is also used to focus the neutron interrogation on particularly
25     suspect regions of interest. For example, information from the X-ray CT procedure is used to employ a large number of small pixels to interrogate high density areas (which are the most likely to contain explosives) and to employ only a small number of large pixels to interrogate
30     low density areas (which are the least likely to contain explosives). We call this use of the X-ray CT information "focussed pixelation."

Characteristics of a typical explosive are:
          Density: 1.2 to 1.8 gm/cc
35            Partial Density of Nitrogen ("N"): 20-35%

Partial Density of Oxygen ("O"):  40-60%

Partial Density of Carbon ("C"):  20-35%

Total Volume:  250-375cc

Although explosives have a clearly identifiable

5   combination of high oxygen and nitrogen molar densities,
the range of a fixed ratio of these respective densities
is not unique to explosives.  NI can extract both the
ratio and relative values of the oxygen and nitrogen
molar densities.  Elimination of the "relative" term

10  requires a normalization factor.  In the present
invention CT is used to measure the physical density of
the object and is thus used to provide a normalization
factor and bounding constraint for NI.

If the chemical composition of the explosive offers

15  an intrinsically useful and abundant species, such as
carbon, its relative density can be used for another type
of normalization.  This later technique has the advantage
that carbon is measured in conjunction with oxygen and
nitrogen and therefore has very similar systematic

20  measurement error distortions.  As it turns out, carbon
is also the most abundant species with the largest $(n, \gamma)$
cross section among ordinary typical baggage contents.
The concentration of carbon is about the same for non-
explosives (such as clothes) and explosives.

25  Accordingly, use of carbon measurements for normalization
of the nitrogen and oxygen measurements eliminates errors
that are common to the carbon, nitrogen, and oxygen
measurements.

The invention employs optimal modeling of neutron

30  source, baggage and detector coupling in a physical
embodiment and optimal algorithmic extraction of detector
data relating to explosives identification.

The primary steps of the technique, to be described
in greater detail below, are that highly localized oxygen

35  and nitrogen density distribution maps are generated for
a typical airline bag to provide respective visual
images, to compute threshold triggers for the signature
of high explosives and to satisfy overall density

consistency checks indicative of explosives in locations which are designated as suspect. The detection process develops a large SNR (signal-to-noise ratio) on a statistical basis in order to ensure a low rate of false

5   negative non-triggers and simultaneously ensure a low rate of false positive triggers so as not to burden the throughput process with redundancy checks and unnecessary manual inspection.

In addition, the inspection system has a minimum

10  number of moving parts to ensure low phonic detector noise and operational reliability. The system is also minimally invasive in the activation sense in that it makes optimal use of the bag geometry and illuminates the bag using a tightly coupled neutron source and a tightly

15  coupled detector array. This tight coupling enhances the event rate which conversely entails a reduced exposure time requirement.

The information from the CT procedure is highly reliable and accurate and is thus also used to constrain

20  and check the somewhat less resolved results from NI. This combination attains a much better performance as compared with either CT or NI by itself.

### Hardware

Figure 1 illustrates an inspection system 1000

25  according to the invention. The inspection system 1000 inspects a bag B using a CT imaging system and a neutron interrogation system. The CT imaging system includes an X-ray source 1110 and an X-ray detector array 1120. The neutron interrogation system includes neutron sources

30  1010 and a gamma detector array 1020. Both the X-ray detector array 1120 and the gamma detector array 1020 are connected to a processor 500, which includes array pulse processing modules/circuitry 512 and 513. The processor 500 is in turn connected to a display 400, which provides

35  information to a system operator. The system operator controls the inspection system via an input device 402. The bag B is passed through the CT imaging system and the neutron interrogation system. As the bag passes between

the X-ray source 1110 and the X-ray detector array 1120,
X-rays pass through the bag and the X-rays transmitted
through the bag are detected by the detector array 1120.

After the bag is inspected by the CT imaging system,
5    the bag passes in between the neutron sources 1010 and
the gamma detector array 1020. The neutron sources emit
neutrons into the bag which react with material inside
the bag.    These neutron-gamma reactions (abbreviated
"$(n,\gamma)$") generate gamma ("$\gamma$") rays which are detected by
10   the gamma detector array 1020.

The X-ray detector array 1120 provides information
to the processor 500 which is used by the processor 500
to create a three-dimensional density map of the bag,
using CT density computation module 510.    The gamma
15   detector array 1020 stores information regarding the
number and energy of gamma rays received by the gamma
detector array.    This information, may be stored, for
example, in histograms.    The information from the gamma
detector array 1020 is used by the processor 500 to
20   compute a three-dimensional map which shows the
concentration of nitrogen, carbon, and oxygen in each
pixel, or voxel, in the bag, using an N, C, and O
chemical species computation module 520.    The computation
module 520 uses density information from the density
25   computation module 510, as will be described in further
detail below.

In addition, information from the density computation
module 510 is used by an NI localization module 530 to
provide region-of-interest ("ROI") information to the
30   gamma detector array 1020 and to the computation module
520.    This ROI information indicates, for example, which
portions of the bag have very low densities and which
portions of the bag have high densities.    Because
explosives are high density materials, the computation
35   module 520 uses the information from the localization
module 530 to focus on the high density areas.    For
example, a large number of small pixels is employed to
interrogate high density areas (which are the most likely

to contain explosives) and only a small number of large pixels is employed to interrogate low density areas (which are the least likely to contain explosives).

CT based information from the CT density computation module 510 and NI based information from the chemical species computation module 520 is provided to a CT and NI image fusion module 540 which fuses the CT based and NI based information together and generates a three-dimensional map accurately showing the concentration of each of the three elements nitrogen, carbon, and oxygen in each pixel of the bag. This map is displayed on the display 400 along with other information.

In certain applications, it may be desirable to include a scale 300 in order to weigh the bag. The scale 300 is coupled to the processor 500 via a signal line 301. The weight of the bag can be determined either physically by such a scale or algorithmically from information provided by the CT imaging system. Weight information based on physically weighing the bag is very accurate and can therefore be used, if necessary, to constrain results derived from calculations. Additionally, the system 1000 may also optionally include a mechanical assembly to reorient the bag as it passes from the CT imaging system to the neutron interrogation system based on the ROI information.

CT Imaging System

The NI system needs density information from CT, primarily in the yz plane, with less accent in the x coordinate direction of the bag to be pixelated. A full purpose CT system would certainly suffice in an algorithmic, pixel and density resolutions sense. However, the density and spatial resolution requirements for baggage inspection are not as demanding as, for instance, medical use CT. Therefore, a special purpose and much more practical and cost effective CT system is used in the present invention. The features are a much reduced spatial and density resolution while at the same time a total throughput of the scanned volume of about 15

liters/sec, for an average exposure of 5-6 seconds per bag, commensurate with a typical baggage size and transit rate.

5    Figures 2 to 4 will be used to describe one suitable CT X-ray imaging system. Another suitable imaging system is described in the United States Patent Application which was filed on October 20, 1994 by Jeffrey W. Eberhard and Meng-Ling Hsiao and entitled "X-Ray Computed Tomography (CT) System for Detecting Thin Objects," the

10   entire contents of which are incorporated herein by reference.

As illustrated in Figure 2, stationary BGO detectors 120 and an X-ray source 110 inspect baggage while the baggage slowly drifts past on a conveyor belt (not

15   shown). A mechanical switch (not shown) or other sensor indicates when the bag is properly positioned between detectors 120 and X-ray source 110.

Figure 2 shows a 6 x 7 detector array. In practice, detector array 120 consists of a 27 x 36 array.

20   A limited view solid angle X-ray fan beam with a two-dimensional aperture scans the bag with X-rays tracking into two-dimensional detector 120 on the far side of the bag. To match NI needs, the X-ray beam is mainly in the z direction with opening angles of more than 30° in the

25   width direction (x) and 40° in the transit direction (y). The detector 120 has 1/2" x 1/2" square BGO crystals over an aperture of 13.5" x 18", to form 972 detector channels. The detectors are connected to BGO pulse processing circuitry 130. The detectors constantly

30   digitize the flux rate of event energies above a certain threshold. The individual channel circuitry employed is similar to that used in conventional CT systems. The circuitry produces a detector frame or state of all 972 channels every 50 msec. This corresponds to 1/4"

35   interval integration for a typical bag. Considering one strip of y direction aligned detectors, this strip is primarily selecting a vertical slice of the bag relative to a point source, with somewhat converging lateral

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surfaces.   Using 36 detectors with about 120 oriented
attenuation/scattering integrals provides a deconvolution
of the slice and consequent density extraction.    A
similar procedure is followed for each y oriented
5   detector strip.   The total output of all deconvolution
results in a three-dimensional pixelation of the bag into
about 100,000 pixels with better than a 1/2" x 1/2" x
1/4" size.

The advantages of this limited viewing angle CT
10  system are that it is immobile, provides complementary
data for the downstream NI inspection in precisely the
required pixelation, has sufficient two- and three-
dimensional resolution, and is much faster than a
standard CT approach due to the limited resolution
15  requirements.

Figures 3 and 4 illustrate the operation of the X-ray
imaging system of Figure 2.   As illustrated in Figure 3,
the bag B passes in between source 110 and detector array
120.     Figure 3 illustrates the X-ray paths at five
20  different positions.       Figure 4 illustrates the
superposition of the X-ray paths at the five positions of
Figure 3.   The information from the superposition of
X-rays is used to create a map w(y,z) indicative of the
density of the bag contents.    Although Figure 4
25  illustrates a two-dimensional density map, in practice,
a three-dimensional density map is generated.   The map
w(y,z) is then normalized, using, for example, the weight
of the bag.

It should be noted that the number of pixels used for
30  the CT process is generally much, much greater than the
number of pixels used for NI.
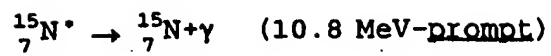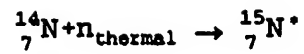
Additional information regarding CT scanning,
hardware, and signal processing may be found in "Computed
Tomography Part I:     Introduction and Industrial
35  Applications," _The Journal of The Minerals, Metals &
Materials Society_, David C. Copley, Jeffrey W. Eberhard,
and Gregory A. Mohr, Vol. 46, No. 1, January 1994, pp.
14-26; _Principles of Computerized Tomographic Imaging_,

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Avinash C. Kak and Malcolm Slaney (IEEE Press 1988); and
_Image Reconstruction From Projections_, Gabor T. Herman
(Academic Press 1980).  The entire contents of these
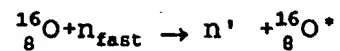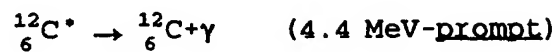publications are incorporated herein by reference.

5                              Neutron Interrogation System

A suitable neutron interrogation (NI) system is shown
in Figure 5.  Figure 5 shows a typical 8" x 20" x 30" bag
B passing between tightly geometrically coupled neutron
sources (NS) 10-1 to 10-7 and BGO detectors 20-1,1 to 20-

10       14,8.  For clarity, Figure 5 shows only 7 neutron sources
and 112 detectors.  In practice, 10 neutron sources are
provided and 600 1" x 1" detectors are provided in a 20
x 30 array.

The neutron sources are formed as an array of

15       individual zetatrons and are operated by electrical
sequencing in the z direction and mechanical scanning
along the y direction.  The neutron sources are
surrounded by moderator material, typically rich in
hydrogen, such as polyethylene or paraffin, with some

20       additional deuterated polyethylene to enhance the
scattering cross section at high-energy reactions.  In
addition, a thin lead liner (not shown) is used
immediately around each zetatron as an effective neutron
multiplier above 10 MeV due to a large number of (n,2n)

25       reactions.  Lead is safe as a low (n,$\gamma$) cross section
choice and has a relatively high $\sigma_{n,el}$ with favorable
kinematics to essentially reflect neutrons due to the
heavy nucleus of lead, thus providing a relatively
enhanced low-energy density, such as in a containment.

30       This is also a blanket of a much larger radius than the
inner liner, for example, 10-15 cm in radius, which is
terminated with lead and acts to produce, by repeated
collisions of neutrons with hydrogen, thermal neutrons
whose diffusion in the bag gives rise to the (n,$\gamma$)

35       signature reactions for nitrogen as shown below:

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$$^{14}_{7}N + n_{thermal} \rightarrow \, ^{15}_{7}N^*$$

$$^{15}_{7}N^* \rightarrow \, ^{15}_{7}N + \gamma \quad (10.8 \text{ MeV-}\underline{prompt})$$

Fast 14 MeV neutrons from the zetatron d+t reaction are used to produce the carbon, oxygen, and nitrogen $(n, \gamma)$ signature reactions as shown below:

$$^{12}_{6}C + n_{fast} \rightarrow n' + \, ^{12}_{6}C^*$$

$$^{12}_{6}C^* \rightarrow \, ^{12}_{6}C + \gamma \quad (4.4 \text{ MeV-}\underline{prompt})$$

$$^{16}_{8}O + n_{fast} \rightarrow n' + \, ^{16}_{8}O^*$$

$$^{16}_{8}O^* \rightarrow \, ^{16}_{8}O + \gamma \quad (6.1 \text{ MeV-}\underline{\text{prompt}})$$

$$^{16}_{8}O + n_{fast} \rightarrow \, ^{17}_{8}O^*$$

$$^{17}_{8}O^* \rightarrow \, ^{16}_{7}N^* + \, ^{1}_{1}p$$

$$^{16}_{7}N^* \rightarrow \, ^{0}_{-1}\beta + \, ^{16}_{8}O^* + \overline{\nu} \quad (\text{slow } \tau = 7.13 \text{ sec})$$

$$^{16}_{8}O^* \rightarrow \, ^{16}_{8}O + \gamma \quad (6.1 \text{ MeV-}\underline{\text{prompt}})$$

$$^{14}_{7}N + n_{fast} \rightarrow n' + \, ^{14}_{7}N^*$$

$$^{14}_{7}N^* \rightarrow \, ^{14}_{7}N + \gamma \quad (5.1 \text{ MeV-}\underline{\text{prompt}})$$
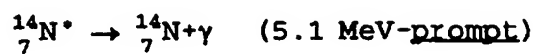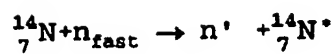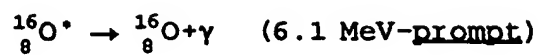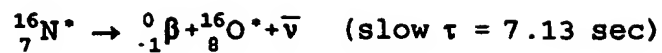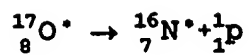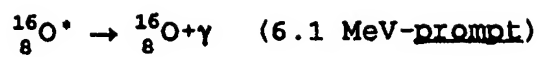
Thus, detection of 10.8 MeV and 5.1 MeV γ's indicates nitrogen; detection of 4.4 MeV γ's indicates carbon; and detection of 6.1 MeV γ's indicates oxygen.

The BGO detector array 20 is pixelated to a maximum
5    feasible level in terms of both cost and physics simplicity. No multiple pixels are provided for summing γ energy because this would introduce a vast layer of data handling software (for example, for pattern recognition and fast timing of coincidences) required to
10   operate at well above 1 MHz incoming events. Multipixel shared energy considerations is not, however, precluded by the DSEX and GSO model to be described below, if desired in a particular application.

A single BGO channel's event processing electronics
15   is shown in Figure 6. The event processing time is about 1 μsec due to the BGO time constant of 300 nsec.

Additional information regarding neutron interrogation may be found in Fast Neutron Physics Part I: Techniques, J.B. Marion and J.L. Fowler eds.
20   (Interscience Publishers, Inc. 1960); Fast Neutron Physics Part II: Experiments and Theory, J.B. Marion and J.L. Fowler eds. (Interscience Publishers 1963); Neutron Physics, K.H. Beckurts and K. Wirtz (Springer-Verlag 1964); Experimental Nuclear Physics: Volume II, E. Segre
25   ed., P. Morrison and B.T. Feld (John Wiley & Sons, Inc.); and Radiation Detection and Measurement, 2d ed., Glenn F. Knoll (John Wiley & Sons). The entire contents of these publications are incorporated herein by reference.

Operation
30   The CT system is used to pre-scan the bag prior to NI. The CT system provides density information and can be used to normalize the total bag weight. In addition, the CT system provides enough intelligence to allow the NI to form a scan and bag pixelation strategy and, if
35   desired, determine the optimal orientation of the bag.

During operation, the bag is stationary for a residence time between the gamma detector array and the neutron sources. The optimal GSO (to be described below)

couplings are enforced and the geometry is not varied to maintain low real time computational loads for the GSOs and to keep systematic errors and their variability to a low level. Some systematic errors due to histogrammed

5    background or peripheral incoherent reactions cause a count rate sensitivity.

The NI data rates and statistical errors are extracted for pulse on and off phases from separate histograms and are passed to a DSEX solver/inverter (to

10   be described below) which employs bag densities and a covariance matrix. This data is presented in terms of contour plots of ratios of species, normalized by the CT information, and consistency checks for partial pixel analysis for CT, and the main CT physical density

15   distribution is expressed in contour maps.

The zetatron neutron sources (NS) are operated at a 10% duty factor and are tightly coupled geometrically to the baggage. The source flux is isotropic and yields 14 MeV monoenergetic neutrons from d+t reactions. Signals

20   from the pixelated wall of BGO scintillation detectors are used in conjunction with individual channel pulse processing and pulse height analysis to create histograms of the secondary flux distribution due to prompt and delayed $(n, \gamma)$ reactions. The $\gamma$ spectra are accumulated

25   in separate histograms for the source on and off phases for reasons of background differentiation. Each of the species carbon, oxygen and nitrogen (the most abundant in passive and explosive materials) has a $\gamma$ energy signature with an associated energy resolution. The energy

30   resolution is dominated by the BGO detector total energy capture efficiency, but the energy resolution is also a function of Compton scattering between the reaction position in the baggage and the detector location due to intervening material.

35   In certain applications it is desirable to perform additional physical measurements prior to CT imaging. For example, the moment(s) of inertia (i.e., lopsidedness) of the bag can be determined prior to CT

imaging to provide additional information to identify suspect regions.

## Data Processing

In the processor, a first Monte Carlo analysis generates a neutron fluence for both fast and thermal neutrons at each location in the baggage. The effects included in this first Monte Carlo calculation are:

1. relative solid angle,
2. measurable and computable deviations from isotropic source fluence,
3. reaction rate and attenuation and scattering based on a real time model of atomic densities derived from a prior CT procedure.

The output of this first Monte Carlo analysis is compactly represented by a coupling matrix relating NS positions and bag-pixels and is addressed in the form of a generalized source-to-bag solid angle, $\Omega_{sb}$.

In the processor, a second Monte Carlo analysis relates each bag-pixel to each detector pixel, at a standard fluence, accounting for:

1. relative solid angle,
2. $\gamma$ secondary baggage induced attenuation and scattering based on a real time CT input,
3. Compton scattering mixing of detector pixels,
4. BGO detector self-attenuation and scattering, related to the total energy capture in one individual crystal block, i.e., one pixel,
5. decay of excited states of non-prompt half-lives.

The output of the second Monte Carlo analysis is compactly represented by a coupling matrix relating bag-pixels and detector pixels and is addressed in the form of a generalized bag-to-detector solid angle, $\Omega_{bd}$.

Both generalized solid angle matrices are referred to below generically as GSOs.

The preceding description relates to fluences $(n/cm^2)$ and $(\gamma/cm^2)$. The detector observations are based on flux (fluence per unit time). A separate integrating detector

channel measuring the neutron flux directly based on, for example, $^3$He for thermal neutrons and $(n,\gamma)$ for fast neutrons is used as a continuous flux calibration standard based on a standard geometry and yields the NS

5    neutron current. The main BGO integrated detectors are calibrated periodically using phantoms.

The observed detector species rates are expressed by the fluence equation $N_d = \sigma \, \rho \, L$. More specifically:

$$\underline{s}\,\Big|_n^{2D/3D}\, \{^{2D/3D}\, \underline{\underline{\Omega}}\Big|_{s\,b}^{3D}\, \sigma_{(n,\gamma)}\} \; \{\underline{\rho}\Big|_b^{3D}\, <L_{bag\text{-}pixel}>_n\} \; \{^{3D}\, \underline{\underline{\Omega}}\Big|_{b\,d}^{2D}\, f_{BGO}\} \; = \; \underline{R}\Big|_{d\,s}^{2D}$$

10   where

$$\underline{\rho}\Big|_b^{3D}\, <L_{bag\text{-}pixel}>_n \;=\; \frac{N_{species}}{bag\_pixel} \; < \frac{L_{bag\_pixel}}{V_{bag\_pixel}} > \; neutron\_track$$

All quantities are superscripted with the number of space dimensions covered, for example, the bag is pixelated in three-dimensions (3D) and the detector is pixelated in

15   two-dimensions (2D).

The equation for $N_d$ is a generic fluence expression for a thin target, where $N_d$, $\sigma$, $\rho$, and $L$ are the observed reaction rate per unit input rate, the reaction partial cross section, the target density and the target

20   thickness, respectively.

The second equation expresses the relationship between neutrons from the neutron sources, a particular pixel, and the gammas detected by the gamma detector array. In more detail, the first term $\underline{s}_n$ is a vector

25   which represents the number of neutrons per second being emitted from the neutron sources. The second term $\underline{\underline{\Omega}}_{sb}$ is a matrix which represents the solid angle between a particular neutron source and a particular pixel (plus additional attenuation and scattering effects indicated

30   above). The third term $\sigma_{(n,\gamma)}$ is the cross section of one of the three elements (carbon, nitrogen, or oxygen) of interest. The fourth term $\underline{\rho}$ is a vector representing the

density within a pixel and the fifth term $<L_{bag-pixel}>_n$
represents the integrated path length of a particular
pixel. The sixth term $\underline{\Omega}_{bd}$ is a matrix which represents
the solid angle between the particular pixel and a
detector array element (plus additional attenuation and
scattering effects indicated above). The seventh term
$f_{BGO}$ represents the efficiency of the detector elements.
Finally, the term on the right-hand side is a vector
which represents the gammas received at the detector
array for each specific source position.

All of the terms in the second equation are known
except for the $\underline{\rho}$ vector. This $\underline{\rho}$ information relative to
attenuation and scattering is provided by the CT imaging
system. Thus, the CT imaging system provides the
information needed to solve the second equation.
Solution of this second equation provides a three-
dimensional map for each of carbon, nitrogen and oxygen.

The equation for $R_{ds}$, which is really three or more
equations relating to each detectable species, is a more
accurate representation than the first equation because
it relates to a thick target in which reactions are
treated on a bag-pixel by bag-pixel basis, with each bag-
pixel being relatively equivalent to the simple fluence
equation. However, there are the mediating factors of
solid angle, attenuation, Compton scattering, and the
like addressed in the more complicated second equation.
The $(n,\gamma)$ cross section $\sigma(n,\gamma)$ is moderated by the GSO
$\Omega_{sb}$. The bag-pixel density and transit length $\rho_b$ and $<L_{bag-pixel}>$, respectively, are expressed more specifically in
terms of species density, per specific pixel, and are
represented as an integral of neutron track length per
transverse geometrical cross section, N $<L/V>$.

The remaining factors to be considered are the NS
rate $ds_n/dt$, the detector observation rate $R_{ds}$ and the BGO
efficiency for $\gamma$ energy collection, $f_{BGO}$. The second
equation is in a matrix form. There are several
quantities which are considered scalers: the $\sigma_{(n,\gamma)}$ partial

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cross sections and the detector efficiency at the proper species energy, $f_{BGO}$.

   Both the bag and the detector are pixelated, the former algorithmically and the latter physically by
5   discrete detectors. Two arrays of all respective bag and detector locations form the density times pixel thickness and detection rate and are vectors. The NS is allowed to move to various inspection locations so its rate is a vector although the actual entries are all equal to the
10   NS neutrons/second rate.

   The remaining matrix quantities, the GSOs, relate phase spaces of the NS to the bag and the bag to the detectors. Both matrices encompass geometric solid angles, attenuation, scattering, and the like, for the
15   respective beam-target process.

   The flux equation can be rearranged to represent more closely its ultimate utilization. Reinterpreting the variables we have:

$$\underline{\underline{\Omega}}\big|_{bd} \ \underline{\dot{\rho}}\big|_{b} = \underline{R}\big|_{ds}$$

20   We call this equation the density solution equation (DSE). The relations to the flux equations are:

$$\underline{\underline{\Omega}}\big|_{bd} = {}^{3D}\underline{\underline{\Omega}}\big|_{b\,d}^{2D}$$

$$\underline{\dot{\rho}}\big|_{b} = \underline{\dot{s}}\big|_{n}^{2D/3D} {}^{2D/3D}\underline{\underline{\Omega}}\big|_{s\,b}^{2D} \ \sigma_{(n,\gamma)} \ \underline{\rho}\big|_{b}^{3D} \ <L>_{n}$$

$$\underline{R}\big|_{ds} = \underline{R}\big|_{ds}^{2D} / \ f_{BGO}$$

25   Note that $d\rho_{b}/dt$ is an equivalent current proportional to the NS rate. The final equation relates the volumetric current to the physical density by simple scalar array division, as differentiated from matrix inversion:

$$\rho\big|_{bag} = \frac{\underline{\rho}\big|_b}{\underline{\dot{s}}\big|_n^{2D/3D} \quad \underline{\underline{\Omega}}\big|_{sb}^{2D/3D} \quad \underline{\underline{\Omega}}\big|_{sb}^{2D} \quad \sigma_{(n,\gamma)} \quad <L>_n}$$

The denominator in this equation is a normalization current for reactions that eventually terminate in the properly detected species, promptly or as half-life decays. It is apparent that the above equations have a relationship to a detector integrating time interval and the time interval's phasing with respect to the NS time domain modulation.

Data is collected in separate histograms for the NS on and off times because background events and dead times are expected to be different. This is not shown specifically but is lumped into the character of $\Omega_{bd}$. The $\Omega_{bd}$ matrix in the DSE relates the number of detector channels, that is, detector pixels, to the algorithmic bag-pixels. A solution exists only if the dimension of the $R_{ds}$ vector is larger than the dimension of the bag-pixels vector.

The term "NS" for neutron source(s) is used in a broad sense to encompass the detailed physics of the intrinsic zetatron NS and the construction of the neutron thermalization blanket. The zetatron quasi point source becomes more extended in the context of thermal neutrons.

Time domain aspects of the DSE account for a slow activation process from exposure start and thermal neutron transients relating to zetatron on and off pulse structure. These time domain features are reflected in the GSOs. The limited zetatron neutron current may be partially bypassed for long-lived states equal to or longer than the bag residence time near the detector, such as oxygen channel events, by exposure prior to insertion of the bag into the neutron interrogation enclosure.

An additional refinement relates to the detector performance and the fact that statistical and limited NS

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rates are related to the statistical errors in $R_{db}$.  The
species peak counts and statistical errors are extracted
by a fit of a Lorentzian distribution superimposed on a
relatively smooth background.  The DSE is transformed
5    into a generalized maximum likelihood expression and
linearized.  This equation is called the DSEX equation:

$$\left\{\frac{1}{\delta R_{ds}} \otimes \Omega_{bd}\right\}_{matrix} \dot{\rho}|_b = \left\{\frac{1}{\delta R_{ds}} R_{ds}\right\}_{vector}$$

The   curly   brackets   represent   the   respective   one-
dimensional   and   two-dimensional   quantities   properly
weighted to account for the detection statistical errors,
10    $\delta R_{db}$.   Standard  theory  leads  to  a  solution  for  the
covariance matrix.  This matrix then makes available the
self  and  correlation  errors  relating  bag-pixels.    The
upshot is a bag density with calculated errors in terms
of  standard  deviations,  i.e.,  a  signal-to-noise  ratio.
15    This  relates  intimately  to  the  number  of  both  false
positives and false negatives at the explosive detection
level.

The GSOs $\Omega_{sb}$ and $\Omega_{bd}$ as well as $<L>_n$ employed in the
neutron interrogation data processing procedure described
20    above require knowledge of the densities in the bag.  The
CT  system  precedes  the  NI  process  and  provides  the
required physical density information.

A   statistical   model   or   equivalent   is   used   to
associate a species density to bag-pixels in order to
25    calculate  the  GSO  matrices.    The  bag  density  final
solution for each species can be iterated in calculating
the GSOs.  Since the GSOs depend primarily on the solid
angle,  it  is  proper  to  inject  an  initial  estimation  of
the  species  densities,  which  for  initial  estimation
30    purposes  can  be  considered  uniform  throughout  the  bag  as
long  as  numerical  convergence  is  guaranteed  for  the

iterative process of recirculating interim density solutions. This is equivalent to a situation in which the structure of the bag is a relatively small perturbation on the GSO's computation, through
5   attenuation and scattering, and the like.

NI does not necessarily cover the signature of all feasible atomic species in baggage. Furthermore, practical considerations relating to BGO detectors or any other type of detector place a limit on the maximum
10  number of physical channels per NI system. These considerations include the total energy collection per individual crystal, i.e., the number of radiation lengths for the crystal. Shared crystal events with partial energy in two or more crystals are not considered a
15  viable solution in this context due to high cost and increased system complexity, but are totally compatible with the underlying model developed for NI and reflected in the DSEX model. This then provides an upper threshold for bag pixelation in the final density solution.

20  An additional function of CT is to enable the normalization of the bag-pixel using a physical density which relates in part to C, N and O. The vast majority of all significant content species are represented by C, N and O. The NI pixels for a typical bag are rather
25  large, therefore a combination of high-density explosive in a small amount and a low-density material (say wool) in a large amount, volumetrically, or either extreme of materials choices, cannot be discriminated on the NI basis alone. A subdivision of NI pixels using CT
30  identifies subpixel regions falling within a range density for explosives. It is not enough, however, to identify regions having a density range corresponding to explosives, the proper oxygen and nitrogen densities must be verified. This is accomplished by a consistency check
35  as follows.

Because explosives have very large densities of oxygen and nitrogen while at the same time relatively little carbon, the ratios of oxygen to carbon, nitrogen

to carbon, and nitrogen to oxygen are monitored based directly on the information obtained from NI. These ratios are vastly different for explosives than for passive materials, so even with a partial pixel volume
5    fill they will indicate the presence of explosives.

Given a certain CNO (carbon, nitrogen, oxygen) count rate and a suspect NI subpixel volume as derived from CT, the consistency check subtracts all of the volume of the suspect density as if it were explosive and finds the
10   remainder pixel volume complement O and N densities. Since O and N are high density for explosives, a false explosive association (false positive) with a high density will cause the remainder to have a negative oxygen and nitrogen density for the pixel volume
15   complement, that is, a false premise of explosive in the subpixel region of the suspect density.

In configurations where camouflage is attempted, the combination of high density CT readings due to the shield density and an absolute lack of any thermal neutron
20   events, due to nitrogen constitutes a vital signature.

A further resolving method is obtained by repixelation of the bag to segregate non-suspicious regions in terms of density to a few in number while dividing the remainder of the bag volume into smaller
25   than average pixel sizes. This CT data biased pixelation is advantageous and is perfectly admissible into the DSEX model. By doing so, the suspect pixel statistics improves and subsequently the consistency checks (using the O/C and N/C ratios and the budget-remainder method
30   described above) obtain a better SNR. Whereas a uniform pixelation would allow only two-dimensional bag-pixels due to the limiting number of detector channels. A focused pixelation based on a CT focused region allows even a local three-dimensional pixel structure with
35   sparse pixelation elsewhere.

## Application Example

Figure 7 is a flowchart which illustrates a specific application example of the present invention.

In step S1, the bag is weighed.   In step S2, moment(s) of inertia (i.e., lopsidedness) of the bag are determined by physical measurement.   Other low and high order mass moments with respect to multiple axes can also be determined, if necessary.

In step S3, CT imaging is used to derive a density for each pixel, or voxel, with high resolution using uniform local exposure.   The CT density information is normalized based on weight and moment information from steps S1 and S2 on a per bag basis.   In certain applications it may be necessary or desirable to perform multiple CT passes.

In step S4, the pixelation for NI is determined. Small pixels, resulting in high resolution, are selected for regions of interest identified by the CT imaging and larger pixels are used elsewhere.

In step S5, neutron interrogation (NI) is performed and histograms of the resulting gamma energies are created.   The spectral contributions for carbon, nitrogen, and oxygen (and any other spectrum distinct species of interest such as hydrogen) are ascertained in step S6, and compensation is made for background events. In step S7, neutron attenuation and scattering in intervening material prior to reaction in each bag pixel is calculated.  In step S8, the neutron-to-target species interaction for neutron reactions and neutron-to-gamma conversion is calculated for each pixel by means of solid angle, attenuation, scattering, and the like.   Step S9 computes the number of gammas emitted from each pixel and their attenuation and scattering in intervening material prior to reaching the gamma detectors.   Compensation is made for detector registration, detector inefficiencies, detector geometrical losses, and detector reaction-based losses in step S10.

In step S11, an initial pass to determine the carbon, nitrogen, and oxygen localization in each pixel is performed using the inversion process described above.

In step S12, numerical constraints are applied to the initial pass from step S11. These constraints include positive density bounds for each pixel for each chemical species separately and constraints for total carbon, nitrogen, and oxygen (plus any other species of interest) with respect to the maximum CT derived physical densities for each pixel.

Step S13 determines if prescribed convergence criteria are satisfied. If not, new attenuation and scattering coefficients are calculated in step S7 and the process is iterated, or repeated. Portions of steps S4 to S6 may also be updated or reperformed. Once the prescribed convergence criteria are satisfied, the CT based and NI based information is used to generate a three-dimensional map accurately showing the concentration of each of the three elements nitrogen, carbon, and oxygen (and possibly hydrogen and others) in each pixel of the bag in step S14. This map is displayed on the display along with other information.

Although the invention has been described above with respect to certain specific applications and implementations of the invention, the scope of the invention is not limited to the specific applications and implementations described above.

For example, other X-ray CT systems may be used instead of the X-ray CT system shown in Figure 2. Alternatively, density information can be provided by a non-CT X-ray system or density information for NI can be based on physical measurements of weight and/or moments of inertia or on approximations based on the make-up of typical bags and stored in a memory. NI can be conducted using single or multiple neutron sources. NI image construction can be based on the spatial configuration of neutron sources or on electronically scanning the neutron sources, or both.

Thus, various modifications, variations and applications within the spirit and scope of the invention will occur to those skilled in the field after receiving the above teachings. Accordingly, the scope of the invention is defined by the following claims.

What Is Claimed Is:

1.    An inspection system to inspect an object for explosives, the system comprising:

          (a)   a CT imaging system for imaging the object, the CT imaging system having an X-ray source and an X-ray detector array;

          (b)   a neutron interrogation system for interrogating the object, the neutron interrogation system having neutron sources and a gamma detector array; and

          (c)   a processor connected to the CT imaging system and to the neutron interrogation system, the processor including

          a density computation module to generate a multi-dimensional density map of the object based on data from the CT imaging system;

          a localization module to provide region-of-interest information for neutron interrogation based on information from the density computation module; and

          a chemical species computation module to generate a multi-dimensional map which indicates the concentration of at least two elements in the object based on information from the neutron interrogation system and on density information from the density computation module.

2.    An inspection system as set forth in claim 1, wherein said at least two elements include nitrogen and oxygen.

3.    An inspection system as set forth in claim 1, wherein said at least two elements include nitrogen, carbon and oxygen.

4.    An inspection system as set forth in claim 1, wherein sizes of pixels used for neutron interrogation vary based on said region-of-interest information.

5.    An inspection system as set forth in claim 1, wherein the chemical species computation module uses the information from the localization module to focus neutron interrogation on high density areas within the object.

6.   An inspection system as set forth in claim 1, wherein said object comprises luggage.

7.   An inspection system as set forth in claim 1, further comprising a scale, connected to said processor, to weigh the object.

8.   An inspection system as set forth in claim 1, further comprising a mechanical assembly to reorient the object as it passes from the CT imaging system to the neutron interrogation system based on region-of-interest information.

9.   An inspection system as set forth in claim 1, wherein said multi-dimensional map which indicates the concentration of at least two elements in the object is a three-dimensional map.

10.  An inspection system as set forth in claim 3, wherein the processor uses carbon measurements for normalization of nitrogen and oxygen measurements to eliminate errors common to carbon, nitrogen, and oxygen measurements.

11.  An inspection system to inspect an object for explosives, the system comprising:

        (a)   a CT imaging system for imaging the object, the CT imaging system having an X-ray source and an X-ray detector array;

        (b)   a neutron interrogation system for interrogating the object, the neutron interrogation system having neutron sources and a gamma detector array; and

        (c)   a processor connected to the CT imaging system and to the neutron interrogation system, the processor including

                a density computation module to generate a multi-dimensional density map of the object based on data from the CT imaging system; and

                a chemical species computation module to generate a multi-dimensional map which indicates the concentration of at least two elements in the object based on information from the neutron interrogation

system and on density information from the density computation module.

12. An inspection system as set forth in claim 11, wherein said at least two elements include nitrogen and oxygen.

13. An inspection system as set forth in claim 11, wherein said at least two elements include nitrogen, carbon and oxygen.

14. An inspection system as set forth in claim 11, wherein said object comprises luggage.

15. An inspection system as set forth in claim 13, wherein the processor uses carbon measurements for normalization of nitrogen and oxygen measurements to eliminate errors common to carbon, nitrogen, and oxygen measurements.

16. An inspection system to inspect an object for explosives, the system comprising:

    (a)  a CT imaging system for imaging the object, the CT imaging system having an X-ray source and an X-ray detector array;

    (b)  a neutron interrogation system for interrogating the object, the neutron interrogation system having neutron sources and a gamma detector array; and

    (c)  a processor connected to the CT imaging system and to the neutron interrogation system, the processor including

        a density computation module to generate a multi-dimensional density map of the object based on data from the CT imaging system; and

        a localization module to provide region-of-interest information for neutron interrogation based on information from the density computation module.

17. An inspection system as set forth in claim 16, wherein sizes of pixels used for neutron interrogation vary based on said region-of-interest information.

18. An inspection system as set forth in claim 16, wherein said object comprises luggage.

19.   A method of detecting explosives in an object, the method comprising the steps of:

(a)   irradiating the object with X-rays and measuring the attenuation of X-rays in the object;

(b)   generating information representing the density make-up of the object based on the attenuation of X-rays in the object;

(c)   irradiating the object with neutrons and measuring gamma particles resulting from neutron-gamma reactions in the object; and

(d)   generating information regarding the presence or absence of explosives in the object based on the measurement of gamma particles in step (c) and on density information from step (b).

20.   A method as set forth in claim 19 further comprising the step of varying sizes of pixels used for neutron interrogation based on density information from step (b).

21.   A method as set forth in claim 19, further comprising the step of focussing neutron interrogation on high density areas within the object based on density information from step (b).

22.   An inspection system to inspect an object for explosives, the system comprising:

(a)   a source of density information for the object;

(b)   a neutron interrogation system for interrogating the object, the neutron interrogation system having neutron sources and a gamma detector array; and

(c)   a processor connected to the neutron interrogation system, the processor including

a localization module to provide region-of-interest information for neutron interrogation based on information from the source of density information; and

a chemical species computation module to generate a multi-dimensional map which indicates the concentration of at least two elements in the object

based on information from the neutron interrogation system and on density information from the source of density information.

23. An inspection system to inspect an object for explosives, the system comprising:

(a) a source of density information for the object;

(b) a neutron interrogation system for interrogating the object; and

(c) a processor connected to the neutron interrogation system, the processor including

a chemical species computation module to generate a multi-dimensional map which indicates the concentration of at least two elements in the object based on information from the neutron interrogation system and on density information from the source of density information.

24. An inspection system as set forth in claim 23, wherein the source of density information is an X-ray CT system.

25. An inspection system as set forth in claim 23, wherein the source of density information is an X-ray system.

26. An inspection system as set forth in claim 23, wherein the source of density information is a memory storing density information.

27. A method of identifying the chemical make-up of an object, the method comprising the steps of:

(a) irradiating the object with neutrons from a neutron source and measuring gamma particles resulting from neutron-gamma reactions in the object in a detector;

(b) estimating neutron attenuation and scattering in intervening material between the neutron source and each of a plurality of pixels representing the object;

(c) estimating neutron to species-of-interest interaction and neutron-to-gamma conversion for each of said plurality of pixels;

(d)   estimating gamma attenuation and scattering in intervening material between each of said plurality of pixels and the detector; and

(e)   determining the concentration of each species-of-interest in each pixel based on the number and energy of gammas detected for each of said plurality of pixels and on the estimations of steps (b) to (d).

28.   A method of identifying the chemical make-up of an object as set forth in claim 27, further comprising the steps of:

calculating new attenuation coefficients and then repeating at least some of steps (a) to (e) until predetermined convergence criteria are satisfied.
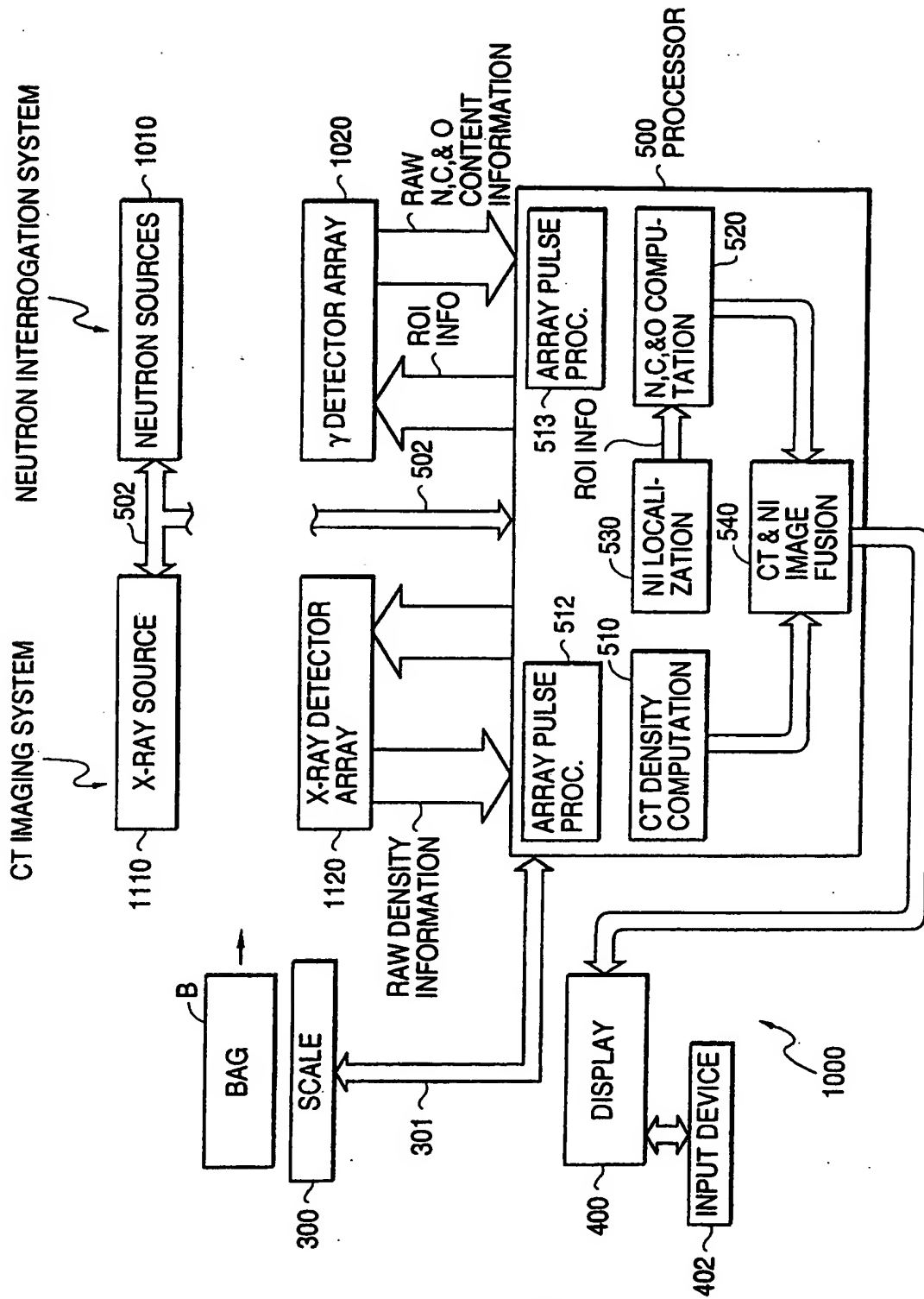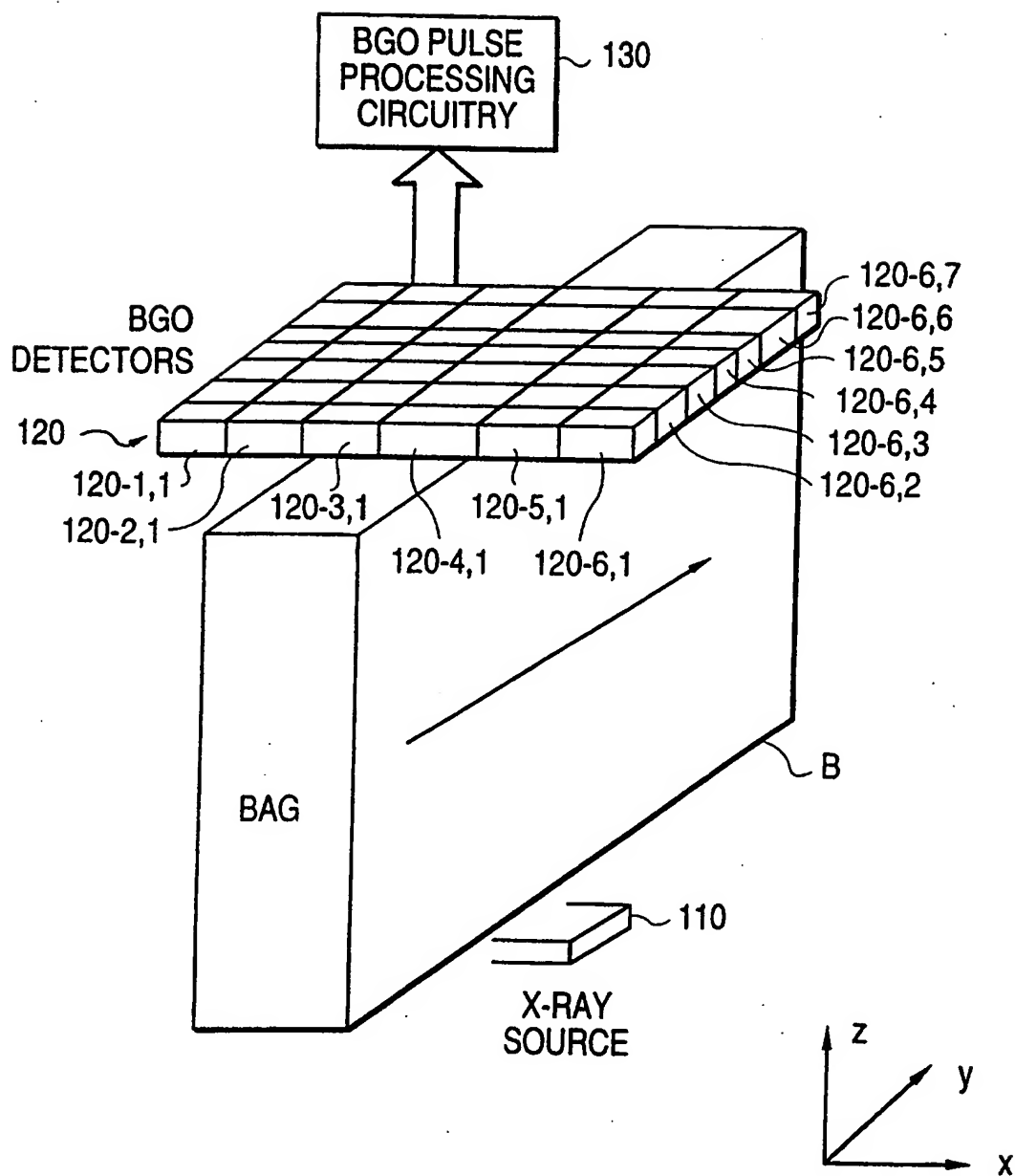
29.   A method of identifying the chemical make-up of an object as set forth in claim 27, further comprising the step of:

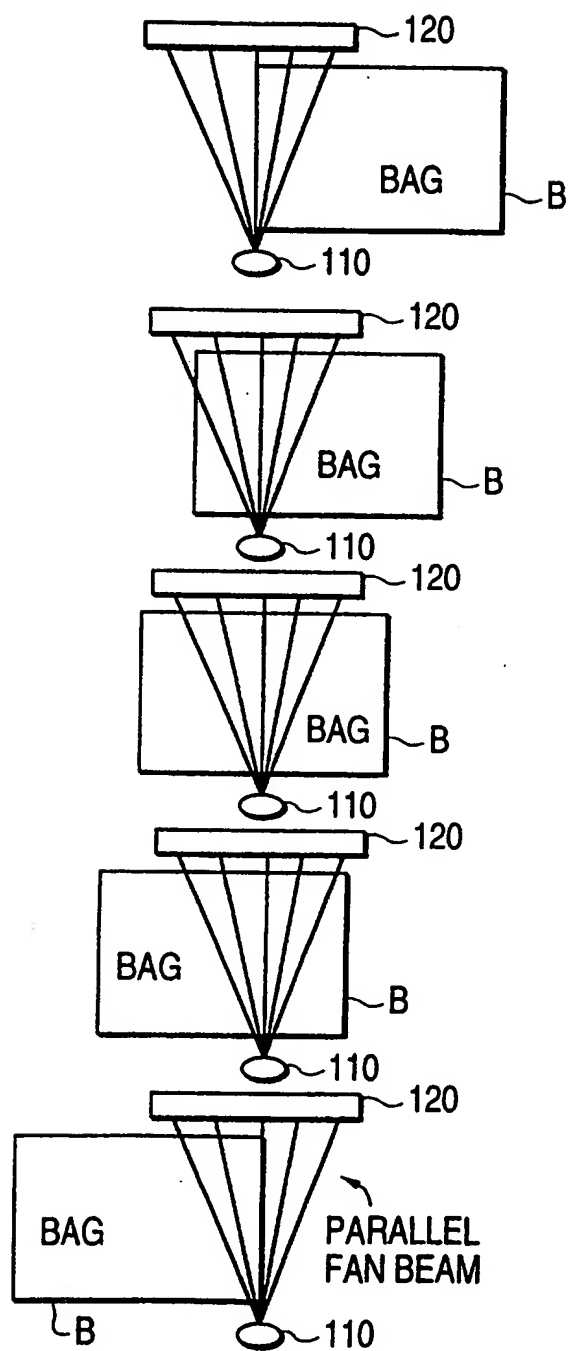irradiating the object with X-rays to obtain density information for said estimations.
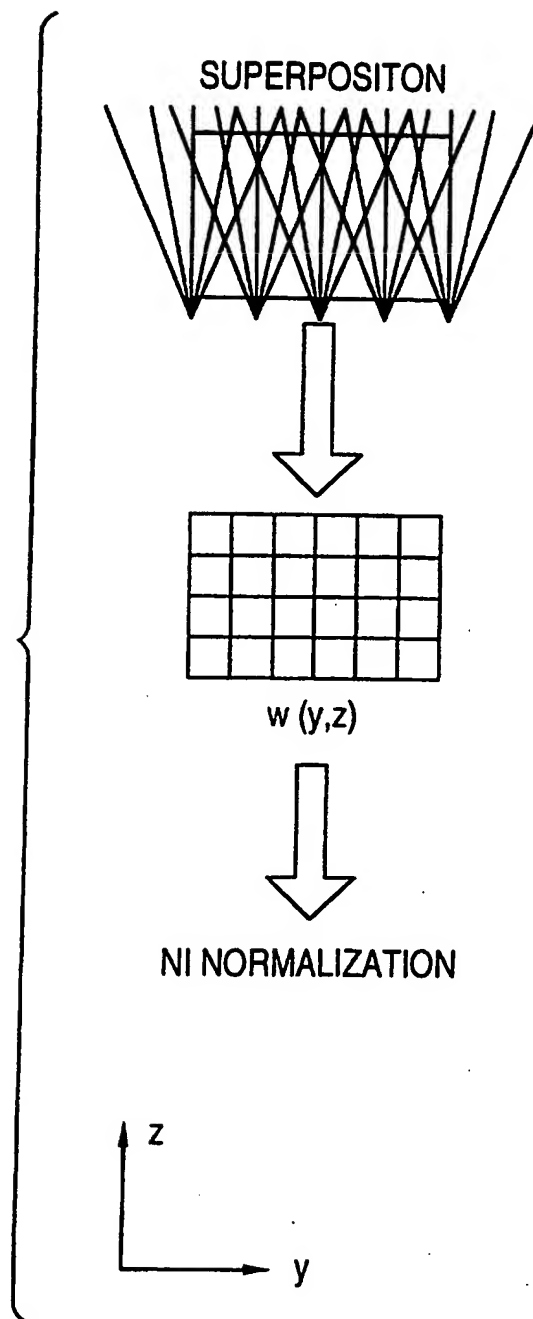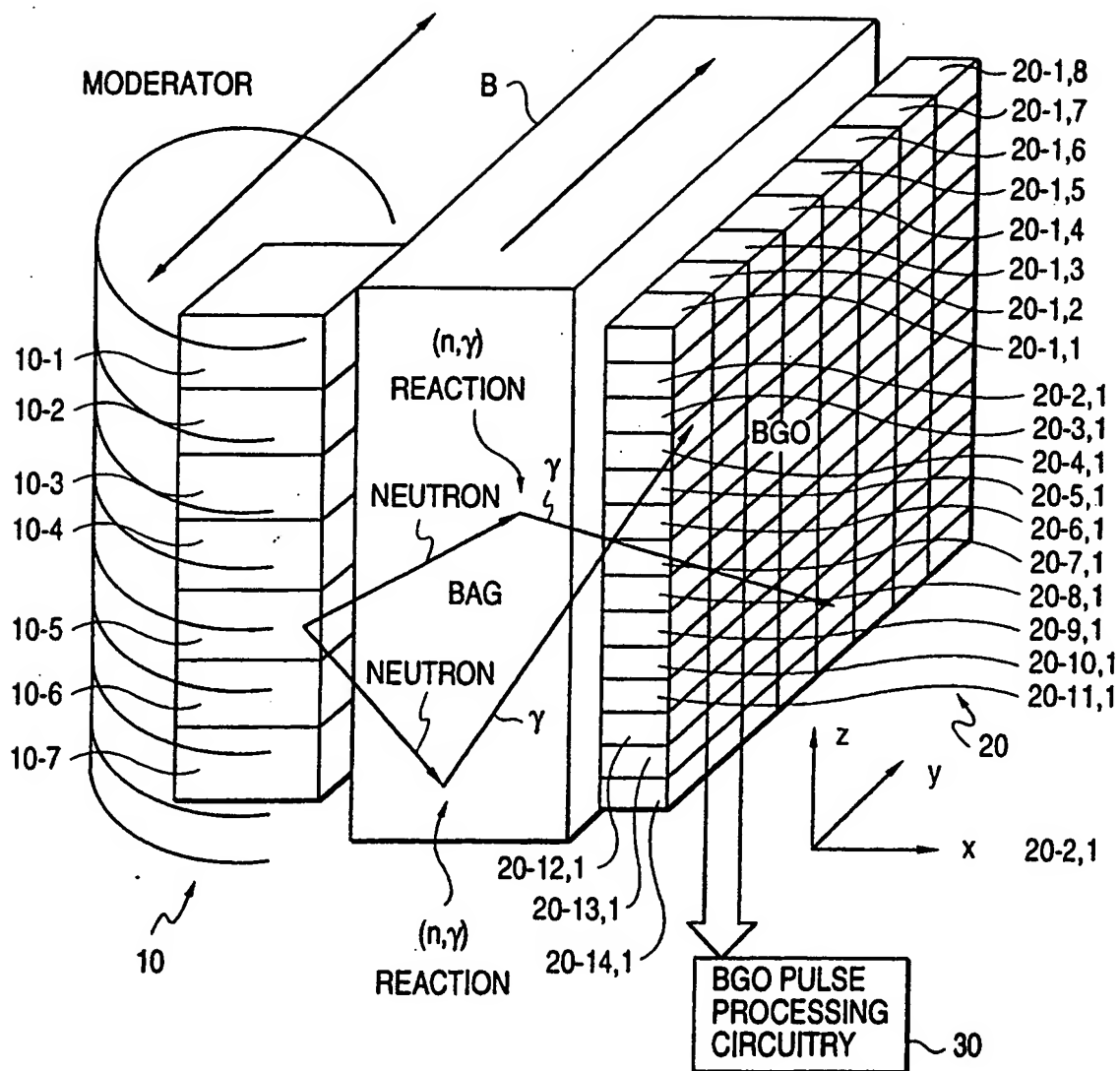
**FIG. 1**
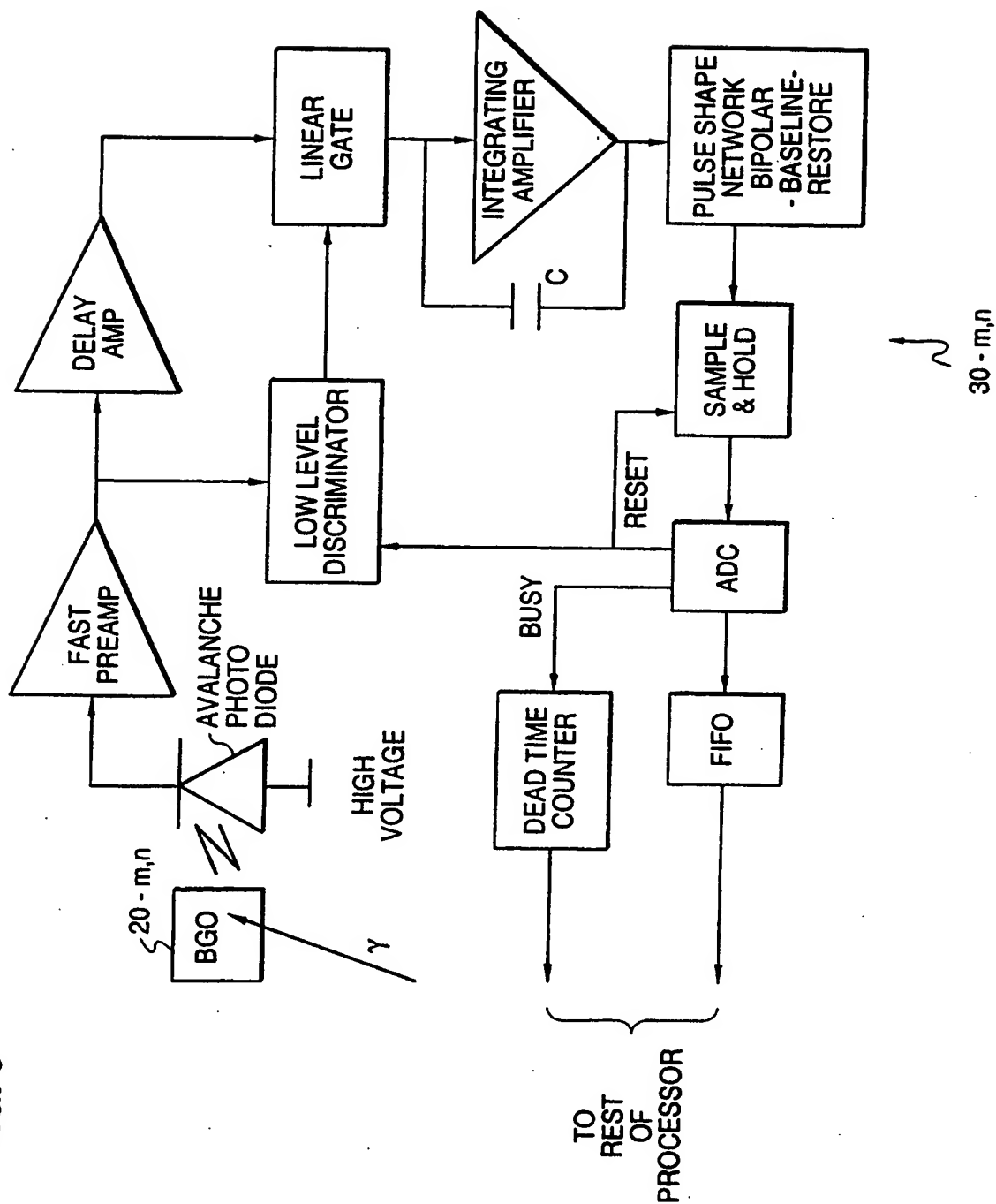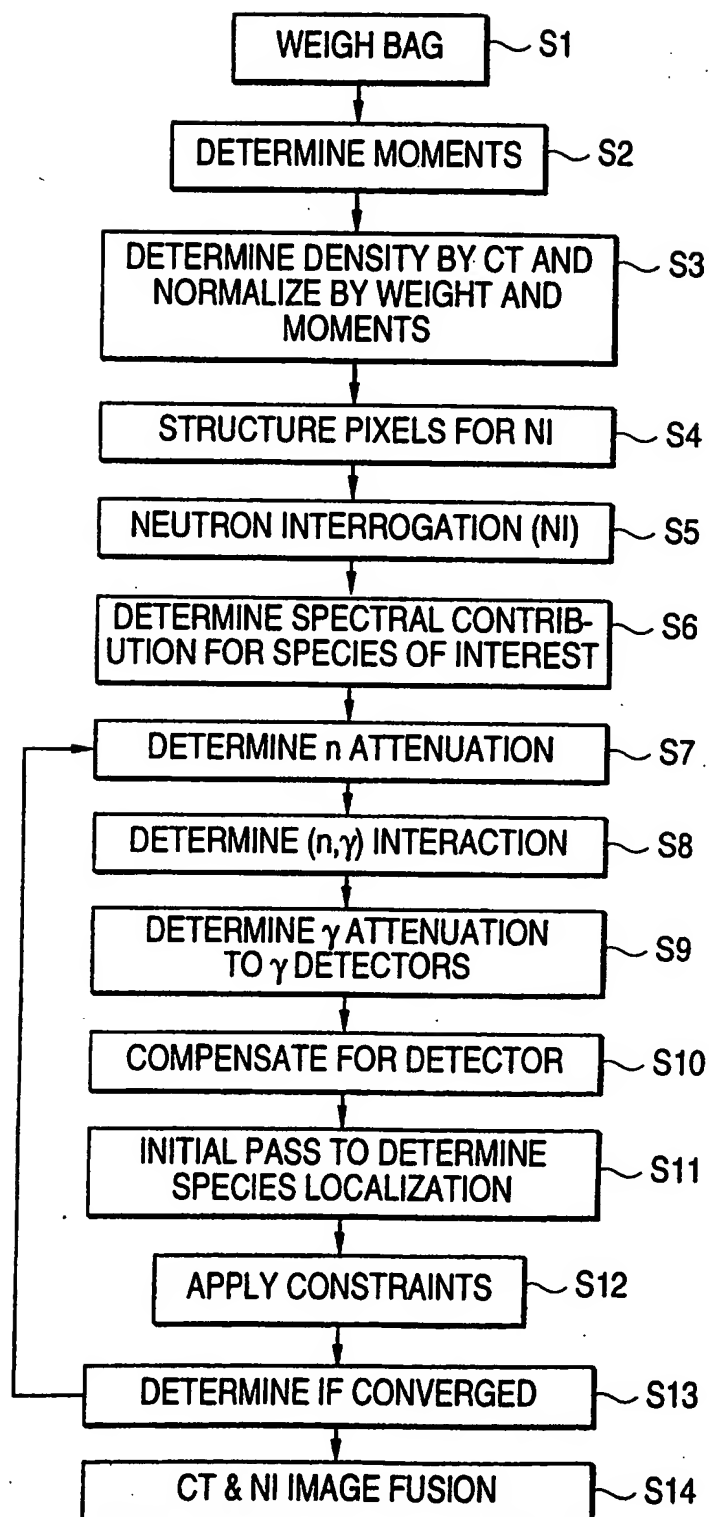
## FIG. 2

# FIG. 3

# FIG. 4

SUPERPOSITON



w (y,z)

NI NORMALIZATION

## FIG. 5

FIG. 6

1/7

## FIG. 7

```
┌──────────────────────┐
│      WEIGH BAG       │──── S1
└──────────────────────┘
          │
          ▼
┌──────────────────────┐
│  DETERMINE MOMENTS   │──── S2
└──────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ DETERMINE DENSITY BY CT AND   │──── S3
│ NORMALIZE BY WEIGHT AND       │
│ MOMENTS                       │
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ STRUCTURE PIXELS FOR NI       │──── S4
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ NEUTRON INTERROGATION (NI)    │──── S5
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ DETERMINE SPECTRAL CONTRIB-   │──── S6
│ UTION FOR SPECIES OF INTEREST │
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ DETERMINE n ATTENUATION       │──── S7
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ DETERMINE (n,γ) INTERACTION   │──── S8
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ DETERMINE γ ATTENUATION       │──── S9
│ TO γ DETECTORS                │
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ COMPENSATE FOR DETECTOR       │──── S10
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ INITIAL PASS TO DETERMINE     │──── S11
│ SPECIES LOCALIZATION          │
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ APPLY CONSTRAINTS             │──── S12
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ DETERMINE IF CONVERGED        │──── S13
└──────────────────────────────┘
          │
          ▼
┌──────────────────────────────┐
│ CT & NI IMAGE FUSION          │──── S14
└──────────────────────────────┘
```

| A. | CLASSIFICATION OF SUBJECT MATTER |
|---|---|

IPC(6)    :G21C 1/06
US CL    :Please See Extra Sheet.
According to International Patent Classification (IPC) or to both national classification and IPC

| B. | FIELDS SEARCHED |
|---|---|

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   376/159, 257

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

| C. | DOCUMENTS CONSIDERED TO BE RELEVANT |
|---|---|

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br>---<br>Y | US, A, 4,671,256 (LEMELSON) 09 June 1987, see entire document. | 1-18,22-26 ----<br>---------- 19-<br>21,27- 29 |
| Y, P | US, A, 5,410,156 (MILLER) 25 April 1995, see cols. 1 and 3. | 1-29 |
| X<br>---<br>Y | US, A, 5,153,439 (GOZANI ET AL) 06 October 1992 see cols. 3, 4, 5, 8, 14, 15, 23. | 19-23,25- 29<br>----------<br>1-18, 24 |
| Y | US, A, 5,200,626 (SCHULTZ ET AL) 06 April 1993, see entire document. | 1-29 |

[X]   Further documents are listed in the continuation of Box C.          [ ]   See patent family annex.

| * | Special categories of cited documents: | "T" | later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention |
|---|---|---|---|
| "A" | document defining the general state of the art which is not considered to be of particular relevance | "X" | document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone |
| "E" | earlier document published on or after the international filing date | | |
| "L" | document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) | "Y" | document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art |
| "O" | document referring to an oral disclosure, use, exhibition or other means | | |
| "P" | document published prior to the international filing date but later than the priority date claimed | "&" | document member of the same patent family |

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 02 FEBRUARY 1996 | 0 6 MAR 1996 |
| Name and mailing address of the ISA/US<br>Commissioner of Patents and Trademarks<br>Box PCT<br>Washington, D.C. 20231 | Authorized officer<br>HARVEY BEHREND |
| Facsimile No.    (703) 305-3230 | Telephone No.    (703) 305-1831 |

Form PCT/ISA/210 (second sheet)(July 1992)*

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y, P | US, A, 5,367,552 (PESCHMANN) 22 November 1994, see entire document. | 1-29 |
| Y | US, A, 5,124,554 (FOWLER ET AL) 23 June 1992, see entire document. | 1-29 |
| Y | US, A, 4,918,315 (GOMBERG ET AL) 17 April 1990, see entire document. | 1-29 |
| Y | US, A, 5,076,993 (SAWA ET AL) 31 December 1991, see entire document. | 1-29 |
| Y | US, A, 5,278,418 (BROADHURST) 11 January 1994, see entire document. | 1-29 |
| Y | US, A, 5,098,640 (GOZANI ET AL) 24 March 1992, see entire document. | 1-29 |
| Y | US, A, 4,229,654 (ARYA ET AL) 21 October 1980, see entire document. | 1-29 |

# INTERNATIONAL SEARCH REPORT

International application No.

PCT/US95/12631

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**Box I   Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)**

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

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**Box II   Observations where unity of invention is lacking (Continuation of item 2 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

   Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**   ☐ The additional search fees were accompanied by the applicant's protest.

   ☒ No protest accompanied the payment of additional search fees.

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A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

376/159, 257

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

I. An inspection system (claims 1-18, 22-26).
II. A method of detecting explosives and chemicals utilizing x-rays and neutrons (claims 19-21, 29).
III. A method of identifying the chemical make-up of an object using neutrons (claims 27, 28).
Within Group I, there is lack of unity between the following independent and distinct species:
A. The embodiment utilizing a CT-X-ray system (claims 1-18, 22-24).
B. The embodiment utilizing a non-CT X-ray system (claims 22, 23, 25).
C. The embodiment utiliizing density information stored in a memory (as set forth in the specification on page 27 lines 27+) (claims 22, 23, 26).
 There is lack of unity under PCT Rule 13 because there is no "special technical feature" common to all of the inventions of Groups I-III which defines the contribution which each of the inventions makes over the prior art (likewise, there is no "special technical feature" common to all of the species defined as A, B and C, which defines over the prior art). In the present case, there is no common "special technical feature" because the independent and/or generic type claims do not define over any of U.S. Patent No. 5,153,439 (Gozani et al ), U.S. Patent No. 5,410,156 (Miller) or U.S. Patent No. 4,671,256 (Lemelson). There is also lack of unity because neither Group I nor Group II as claimed, require the particulars of Group III as claimed. Group III has separate utility such as in determining the amount of fissile material in nuclear reactor waste or in ore or, it can be used in bore hole detecting. There is also lack of unity between Groups I and II because the apparatus of Group II, as claimed can be used to practice another and materially different process, such as determining the presence of specific elements in bulk material on a conveyor.